REVIEW PAPER

A Survey on Channel Measurements and Models for Underground MIMO Communication Systems

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Abstract: The high reliability of the communication system is critical in metro and mining applications for personal safety, channel optimization, and improving operational performance. This paper surveys the progress of wireless communication systems in underground environments such as tunnels and mines from 1920 to 2022, including the evolution of primitive technology, advancements in channel modelling, and realization of various wireless propagation channels. In addition, the existing and advanced channel modeling strategies, which include the evolution of different technologies and their applications; mathematical, analytical, and experimental techniques for radio propagation; and significance of the radiation characteristics, antenna placement, and physical environment of multiple-input multiple-output (MIMO) communication systems, are analyzed. The given study introduces leaky coaxial cable (LCX) and distributed antenna system (DAS) designs for improving narrowband and wideband channel capacity. The paper concludes by figuring out open research areas for the future technologies.

Keywords: leaky coaxial cable (LCX); long-term evolution for metro (LTE-M); multiple-input multiple-output (MIMO) systems; propagation modeling

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I. INTRODUCTION

In recent decades, the underground communication community has begun to embrace short-range wireless communication technology as an important element of their strategy for improving the productivity and safety. Through the use of multipath propagations, leaky coaxial cables (LCXs) have lately emerged as crucial technique for boosting the capacity of wireless local area networks (WLANs) in conventional domestic, industrial, and commercial applications. The consideration of LCX both as transmitting and receiving antenna has many valuable applications in wireless communication networks, such as for the high-speed railways, exact location of train, automatic highway, underground conveyance, and communication-based-train-control (CBTC) systems [1–3]. Usually, one LCX is used as one antenna. Therefore it requires more than one LCX to configure a MIMO system. [4] proposes a single LCX-based MIMO system which can function as two antennas when different radio frequency signals are fed to each end of LCX. Therefore, the single LCX-based MIMO can reduce the system cost and space requirements to configure MIMO system.

At very high frequency (VHF), the wireless system performance in underground carriage tunnels and mines is found to be very poor because their inner structures induce the waveguide effect. Traditional distributed antenna system (DAS)-based channels have played a significant role in underground communications over the last five decades, but they are no longer compatible with newly evolved technologies and wireless standards that provide much higher efficiency and better capabilities, such as integrated data and voice. In literature, numerous studies have been perceived to improve the data rates and capacity of a channel for long-term evolution in metro (LTE-M) systems. Recent interests in deployment of next generation wireless communication systems in underground tunnels has stemmed from: (1) the potential to enhance the tunnel environment productivity and efficiency through efficient voice communication, better approach towards the management of data system, and automatic dispatch [5–9], (2) recent models for wireless personal area network (WPAN) devices and for the short distance wireless communication networks. The separating distance between antennas has a reasonable impact on the outcome of MIMO channel; thus by properly adjusting this distance and other factors, a reliable and stable performance can be acquired which is important for the underground radio communications.

1.1 Main Contributions

None of the aforementioned publications tackled the modeling requirements of LCX- and DAS-based massive MIMO channels in mine and tunnel environments. In this review, we discuss not only the importance of new technology, but also the efficient developed models for channel propagation in underground mines and tunnels. More precisely, the major contributions are as follows:

1. Introducing a New LCX-based Channel Classification: Our intention is to bring earlier research into consideration, classify gaps and directions, and summarize achievements. We interrogate the factors which have greater influence on channel performance and introduce different models used to explain propagation characteristics of a MIMO channel.
2. Performance Analysis single-input single-output (SISO) and Massive MIMO Channel Applications: We consider the extension of SISO channels to high-speed train (HST) massive MIMO channel applications to fulfill the urge of service stability and improvement. To examine the potentials of massive MIMO systems, we provide some modern developments regarding its applications in real time-mine and tunnel environments, such as Metro.
3. Specifying Potential and Research Recommendations: In order to specify the potential techniques to lift the performance of massive MIMO systems, we propose suggestions and emerging ideas for future research directions in wireless communication field.

The rest of the paper is structured as follows. In Section II, a concise review about evolution in wireless communications and factors which has significant influence on wireless propagation characteristics is demonstrated. In Section III, we present deterministic and stochastic channel modeling schemes. The future trends and challenges for upcoming research problems are discussed in Section IV. Finally, Section V concludes this survey.

II. DEVELOPMENT OF WIRELESS COMMUNICATION IN CONFINED ENVIRONMENTS

2.1 Background and Evolution of Wireless Communication

In the early days of wireless communication in confined environments such as underground tunnels and mines, the communication system was relying on experimental study without any empirical understanding and theoretical modeling efforts. The initial incentive for underground communication was focused on facilitating safety purpose in mines or tunnels by executing human-to-human communication. As underground communication system has progressed, men-to-machines and further machines-to-machines communications have been accomplished to meet the productivity and effective goals. The wireless signals when they travel from transmitting antenna (Tx) to a receiving antenna (Rx), they undergo various propagation phenomena such as diffraction, reflection, refrac-

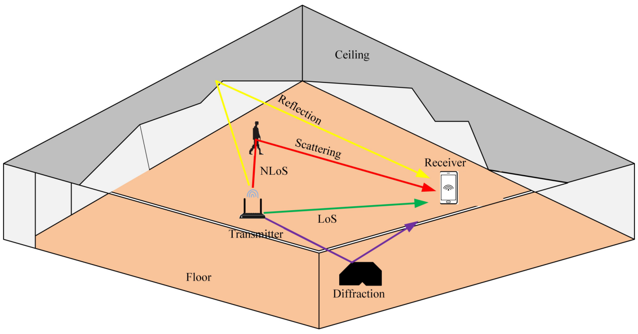


Figure 1. *Basic wireless propagation phenomena in confined environment.*

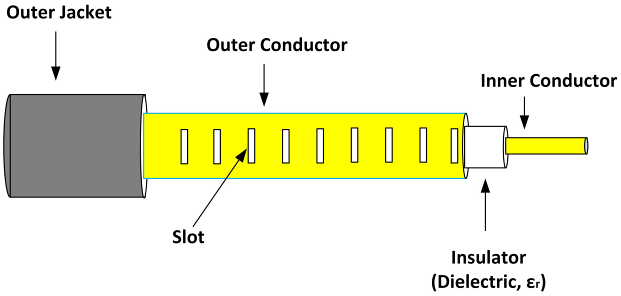


Figure 2. *Leaky coaxial cable inner structure with slots, insulating and conducting sheets.*

tion, and scattering, as shown in Figure 1. Therefore, the interaction of signals through surroundings may cause disturbance and follow many paths between Tx to Rx.

In 1899s, extremely low-frequency (ELF) signals were investigated by N. Tesla, and the earth was exploited as a transmitting medium to deliver worldwide messages [10]. Interest about wireless communications in underground environments has evolved in the late 1920s after the first pioneer of radio propagation was attracted towards the potentials of Through-The-Earth (TTE) wireless communication. It lasted until the 1940s, when the US Mines Bureau started offering various services, including as TTE signaling systems and current radio carriers for emergency operations and routine communications in mines [11]. In 1940s, because of the limitations of bulky mobile equipments and low data rates, the initial research of wireless communication in mines and tunnels was temporarily ceased.

Generally, Through-The-Wire (TTW) signals go all the way through the twisted pair, coaxial cable, trolley, and optical fiber against the outer surface or within the tunnel to reach the mobile apparatus, emergency operations, and routine communications in mines. Since one aspect of TTW signaling scheme is wireless and the other one is wired, it is mostly recognized as semi-wireless or hybrid system. For the public benefit and safety, distributed antenna systems and leaky feeders were designed in the 1950s and 1960s to increase the coverage range of very-high-frequency (VHF) radio communications for considerably shorter subterranean transport tunnels observed in various metropolitan areas [10]. In 1960s, the Government and safety panels in North America and Europe sparked security concerns in order to promote the mining industry and build better communications with the people working there by implementing wireless systems based on leaky feeder and VHF-FM portable radio systems [11]. The leaky feeder or leaky coaxial cable (LCX) is a widely utilized TTW technique for communications in underground environments. The cable is named as leaky due to carrying slots or gaps on its external conducting sheath, permitting signals to flow out or into the cable beside its full length, as shown in Figure 2. Due to the outflow of signals, line amplifiers need to be injected at fixed intervals, usually after every 250 to 450 m. The main drawbacks of LCX systems are fixed infrastructure, challenging maintenance, short coverage, and limited capacity, i.e., the area of a mine from where the minerals need to be extracted [11].

Through-The-Air (TTA) at UHF/super-high-frequency is one widely used wireless communication technique in underground mines and tunnels. It is proficient in offering numerous applications such as tracking of mineworkers, two-way data and voice communications, video surveillance, remote sensing, and so on. In early 2000s, the mine industry was fascinated with low data rates technology, for example, passive-RFID (about 1 m), active-RFID (about 10 m), ZigBee, and systems for high data rates (ultra wideband) because they deal with low power, short range, and positioning competency. These techniques can support different applications of sensor networks. The objective for device-to-device (D2D) communications is to deliver direct communications, low rate in online connections, and low power [12]. A large number of studies are underway to address the latest requirements of the fifth generation (5G) networks. Table 1 provides a complete performance evaluation of the listed wireless technologies under different

Table 1. *Functional wireless technologies for underground railway systems.*

Technology Type	Data Rate	Speed Limit	Operating Frequency	Maturity
LTE-R	50 Mbps/12 Mbps	<500 km/h	450/800/1400 MHz	Evolving
GSM-R	170 Kbps	<500 km/h	930 - 934 MHz (DL) 885 - 889 MHz (UL)	Life ending 2025
LTE-M	50 Mbps/10M bps	<500 km/h	1.785 - 1.805 GHz	Evolving
WLAN	12 Mbps/12 Mbps	<1000 km/h	2.5/5 GHz	Widely practiced
28 GHz mmWave	2000 Mbps	<400 km/h	27 GHz	Evolving
38 GHz mmWave	8 Mbps/4 Mbps	<500 km/h	37.1 - 38.5 GHz	Matured

high-speed environments. However, the highest speed limit up to 500 km/h of aforementioned techniques is even hard to attain, whereas the vacuum tube high-speed flying train (vactrain) can achieve a higher speed up to 1000 km/h. In order to tackle 5G MIMO system requirements, the standardized article 3GPP TR 38.913 [13] specifies that 5G NR can achieve a highest speed up to 500 km/h.

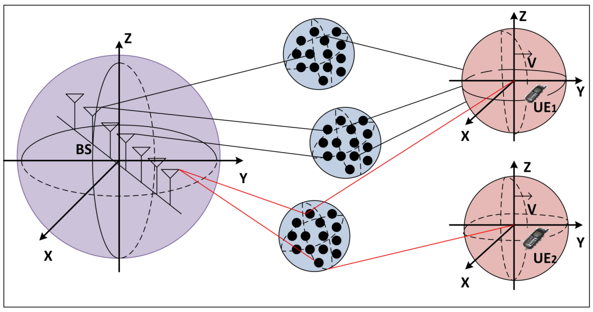


Figure 3. *A standard diagram of massive MIMO channel spatial characteristics.*

2.2 Antenna Setup and Challenges

In traditional systems, the base station (BS) cannot accomplish beamforming gain until it secures a transmission link across the terminals. To begin, the BS broadcast pilots, which the terminals use to assess their channel responses. Afterwards, the BS receives terminal estimation, which is quantized and transmitted back to it. In addition, the frequency-division duplexing (FDD) has limited applications in massive MIMO radio channels due to the time-frequency resources required for pilot broadcasting in the downlink (DL) scale with the number of antennas and the number of channel responses that must be predicted on each terminal. The time required for pilot broadcasting can improve channel coherence time in large antenna arrays [14, 15]. Allowing terminals to transmit pilots to the BS through time-division duplexing (TDD) is a substitute for massive MIMO channels. TDD works on the principle of channel reciprocity, in which uplink (UL) channels are used to estimate downlink (DL) channels. This removes the involvement of channel state information (CSI) in decision making. Pilot contamination and reciprocity calibration are two drawbacks of TDD: the former arises in multi-user setups when a non-orthogonal pilot technique is used, causing the reserved user's channel estimate to be contaminated by other users who are consuming the same pilot; the latter is required for various transfer characteristics in UL/DL. Pilot decontamination and reciprocity calibrations are analyzed in [6, 7], but no ideal solution has been discovered so far. At the Tx side, multi-user interference can be reduced by adapting typical single-stream beamforming algorithms to handle multiple streams. For a small number of antennas, precoding using Minimum Mean Square Error (MMSE) or Zero-Forcing (ZF) is quite useful. On the other hand, the dependence on channel inversions may increase the power load resulting in complexity within extremely large arrays [8].

The simplest approach known as matched filtering (MF), includes Maximum-Ratio-Combining (MRC) in the UL and Maximum-Ratio-Transmission (MRT) in the DL [15]. Tomlinson-Harashima-Precoding (THP) [16], Vector-Perturbation (VP) [17], and Dirty-Paper-Coding (DPC) [18], all have attractive features, but they are either too expensive to implement in practical applications or deliver gain that is difficult to justify due to higher computational complexity. By considering MF, the array size intended to attain

Signal-to-Interference-Ratio (SIR) which is quite high in magnitude (at-least double) than that of ZF precoding [19], more research into cost-efficient solutions is further required. This is also illustrated in [20] for Block Diagonalization (BD) case. Maximum Likelihood (ML) approach is the best option for handling data streams in a conventional system, but it's complexity rises exponentially along the number of streams. This is the actual reason, why detection and parameters estimation are two major issues in massive MIMO channels. Figure 3 represents a generic structure of these novel characteristics from the antenna arrays and multipath components. Suboptimal MF, MMSE, and ZF have low cost, but they cannot achieve the complete receive-diversity gain of maximum likelihood approach [8]. MMSE with Successive-Interference-Cancellation (SIC), Tabu-Search (TS) [21], Block-iterative Generalized-Decision-Feedback-Equalization (BI-GDFE) [22], Fixed-Complexity-Sphere-Decoding (FCSD) [23], and Likelihood-Ascent-Search (LAS) [24] were developed as a result of such performance complications tradeoff. For large arrays, matrix inversion in BI-GDFE and MMSE-SIC is computationally expensive, and MMSE-SIC outperforms matrix-inversion techniques like LAS and TS [8]. This suggests that further investigation is required, maybe in the direction of low-density-parity-check (LDPC) codes or turbo-codes in decoding settings and iterative detection [8, 19]. It is aimed in [14, 25] that, due to the law of large numbers, the MIMO channel becomes more difficult to offer each subcarrier with similar channel gain. The same findings have been also stated in [6] under the perspective of FBMC, and the authors named it as self-equalization, and it can further contribute towards the reduction of the number of subcarriers. Another advantage of a massive MIMO system is having a higher spatial degree of freedom and can employ the same frequency band. Table 2 defines such shortcomings, their existing solutions, and moreover each one is explored along their side effects. The majority of massive MIMO channel research is based on the assumption that the MIMO channel is independent. However, in the reality, the above supposition is quite hard to comprehend when the number of antennas are quite large.

2.3 Channel Sounding

It is worth noticing that propagation scenario may be considered as a superposition of several propagation paths, where the Rx senses the combined radiated field produced by all of them. Moreover, the Rx can identify propagation paths using one of three methods:

1. by considering the time-division-multiplexing (TDM) technique to transmit a single element at a given time,
2. by utilizing the frequency-division-multiplexing (FDM) technique to transmit signals at different frequencies,
3. or by using the distinctive code word to each element, named as code-division-multiplexing (CDM).

The decision of which multiplexing approach is suitable, can be decided by the feasibility of hardware as well as the required precision of channel measurements. Here, we go through the most common sounding approaches and evaluate their benefits and drawbacks in terms of the characteristics they may provide.

2.3.1 Fully Switched Channels

Fully switched channels have a certain attraction in MIMO characterization since only one set of RF front end needs to be characterized. This technique might be well known for another reason - it is basically a SISO sounder with multiple switches on the Tx side and one switch on the Rx side. As a result, current sounder can be easily modified to accommodate more complicated antenna designs. This category includes the broadband channel sounder developed by Helsinki University of Technology (HUT) [32], which operates at frequencies of 2.1 GHz and 5.3 GHz. In MIMO systems, this sounder utilizes a pseudo-random noise sequence for a broadband excitation and fast microwave switching at both the transmitting and receiving sides. The switches may switch up to 32 components simultaneously, allowing a high level of MIMO complexity. Because the time required to complete one full measurement cycle determines the maximum rate of change in environment, the sum of the antenna numbers can seriously limit the condition in which a channel sounder can be used. Moreover, if the MIMO system has few components, a large Doppler frequency can be accommodated. As a result of the low impulse response length, only the channels with a low response can be accurately monitored. Another difficulty that

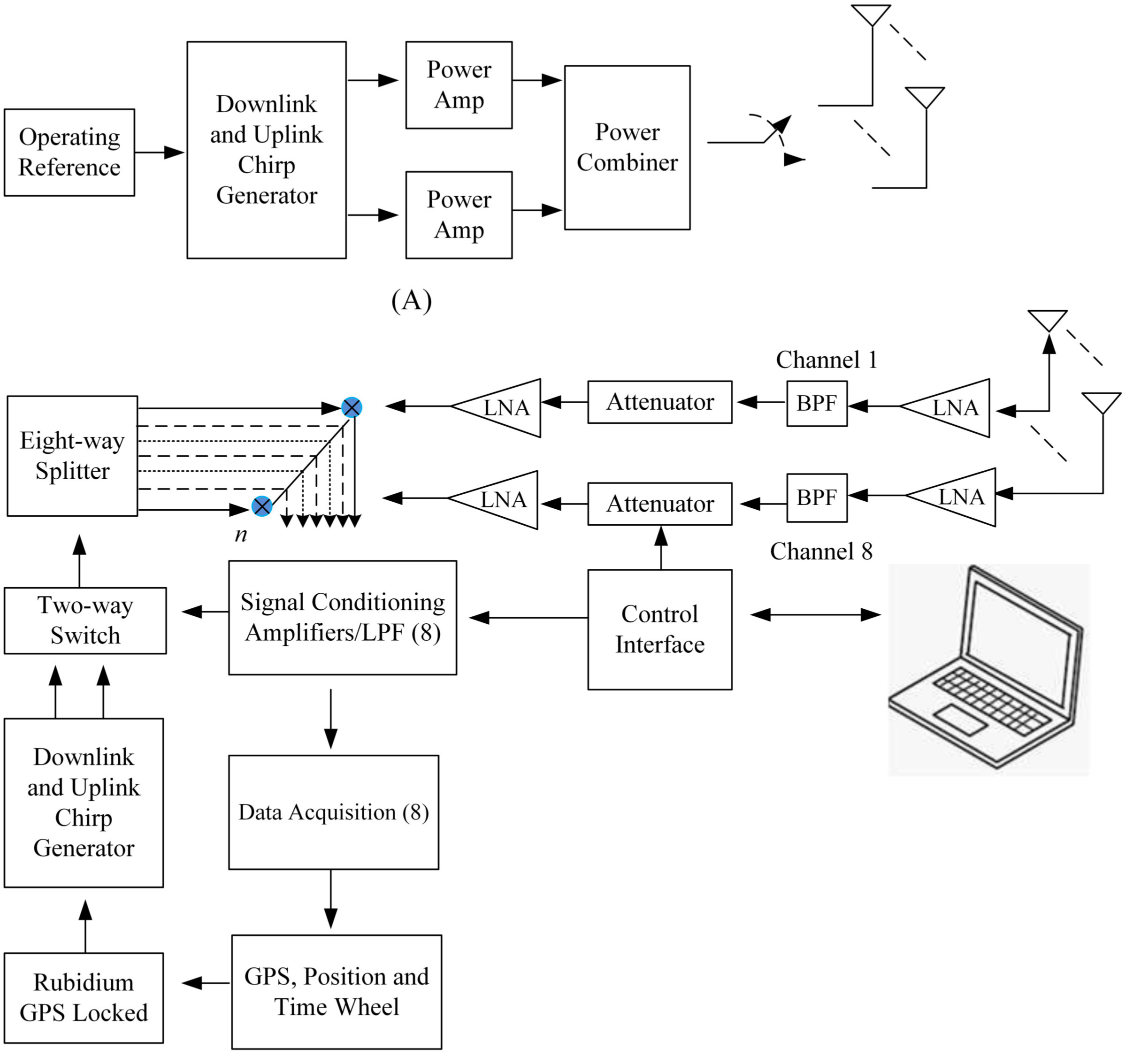
Table 2. *Different challenges and solutions for multiple antenna channels in 5G.*

Research Aspect	**Issue**	**Solution**		**Drawback and Side Effect**	**Ref.**
Antenna features	Front-Back Ambiguities	Dense Multidimensional Executions		a). Restricted to indoor environments b). Increases coupling effect c). 3D-array have limited effectiveness	[5, 6]
	Antenna Coupling	Multi-ports Impedence Matching RF Networks		a). Causes ohmic losses b). Reduces bandwidth c). Not entirely understood for higher M	[5–7]
Propagation	Clusters Resolution	No precise solution investigated so far		Open question for future research	[8]
	Channel Modeling	a). Sophisticated Analytical Method b). A Realistic Empirical Method		Recently under development	[9]
Transceiver Structure and Design	CSI Acquirement	BS transfers Pilots to given Terminals by FDD		Restricted via coherence time of channel	[7, 15]
		Terminals sends Pilot to BS via TDD		Channel cooperative calibration	[26]
				Pilot contamination problems	[27]
	Precoding (in DL}	Linear Precoding Techniques	MMSE ZF	a). Higher average transmitted power b). Computationally substantial for large M	[8, 19]
			MF	a). Higher M mandatory for a given SIR b).Having error floor as M escalates	[8]
			BD	Cost-competent strategies are required	[20]
		Non-linear Precoding Techniques	DPC	Enormously costly for concrete developments	[18]
			THP VP	Expanded Complication is tough to rationalize	[16, 17]
	Detection (in UL)	Random Step Search Method	Bi-GDFE MMSE-SIC	Computationally heavy for higher M	[22]
		Random Step Search Method	LAS TS	Much complicated than the MMSE-SIC	[24, 21]
		Tree-based Algorithm	FCSD	a). Best fit for the $M = K$ case b). 1000x more complicated than TS	[23]
			SD	Complication is exponential in M	[28]
Hardware	Power Deplition	Dedicated, Parallel Baseband Signal Processing		Open question for future research	[29]
	Phase Noise	Smart PHY Transceiver Algorithms		Efficiency yet to be verified	[29]
	Proof-of-Concepts (POC's)	Experimental Evaluation, Tested & Prototype		Merely basic competency demonstrated	[30]

emerges with completely switched systems is the large amount of data that must be stored in a short period of time. During the sounding period, the MEDAV RUSK, for example, is capable of data storage rate up to 320 Mb/s [32].

2.3.2 Semi Switched Channels

A semi-switched system with parallel Rx channels and a switched Tx was built by the University of Durham [33]. As the Rx is activated in parallel, the amount of time it takes for all sounding channels is limited by the time it takes to switch between the Tx antennas, rather than the sum of the Tx and Rx antennas. As a result, a better understanding between the delay spread and higher Doppler frequency is possible. The underlying method, as well as the challenges of creating an accurate portrayal of the environment, are briefly explored in [31]. It should be noted that both the Tx and the Rx are related to downlink and uplink chirps as shown in



(A)

(B)

Figure 4. *Semi switched channel sounding block diagram, reorganized from [31].*

Figure 4. The sounder can measure two frequencies at the same time, which correspond to the downlink and uplink of a paired channel spectrum, i.e., UMTS. Because the Rx hardware is replicated rather than shared among numerous antennae elements, it is feasible to connect two Rx blocks to a single antenna element and measure both downlink and uplink at the same time.

2.3.3 Fully Parallel Channels

In [34], an intriguing approach is provided for practicing the whole frequency range to differentiate transmitting antenna elements. The method works by splitting the frequency range into M sub-bands, which are then separated into N frequencies and allocated to each transmitting device in a cyclic manner. The frequency difference among antenna elements is $\Delta f = \Delta F/N$, and the frequency spacing of tones in a particular transmitting antenna is $\Delta f = B/M$, however in practical cases, a lesser shift is used to prevent the effect of a direct current offset. The maximum delay spread that may be measured using this approach is set by $1/\Delta F$, while the length of sounding for each snapshot of channel is determined by $1/\Delta f$. A discrete Fourier transform (DFT) operation is used at the Rx to demultiplex the signal, resulting in an interleaved channel transfer functions (CTF) averaged over the time of $1/\Delta f$. As a result, the time duration intended for a measurement campaign is not much different from the semi-switched system, and has the drawback of requiring several RF transmitters.

2.3.4 Hybrid Channels

A hybrid system may be created by combining methods such as the semi switched technique with the completely parallel approach. A MIMO system for estimating the transfer functions of a 16×32 broadband MIMO sounder is described in [35]. In this system, the transmitting antennas are arranged in parallel, and the receiving antennas are switched in four simultaneous measurements. The Tx antennas are organized in a 4×4 grid, while the receiving antennae are arranged in an 8×4 grid, with a dummy antenna configuration to overcome mutual coupling effect at the grid boundaries. To handle the enormous volume of data achieved by this operation, the channel utilizes several disks, one for each receiver.

2.4 High-Speed Train (HST) Channels

High-speed train (HST) channels are precisely characterized through their non-stationary characteristics, because of the fast speed of trains. HST scenarios are supposed as one of the distinctive scenarios in the 5G communication networks. Considering the excessive speed of trains such as 500 km/h, the channel modeling of future HST needs to tackle the advanced level challenges, i.e., high Doppler shift, non-stationarity, rapid handover features, and adjustment to different HST propagation scenarios, including tunnel, station, etc. The channel models, for example, the IMT-Advanced [36] and WINNER II [37] present the corresponding channel models under the condition of fast-moving vehicle scenarios. By applying the similar HST model structure in other environments, the IMT-Advanced and WINNER II models can assist in speed increment up to 350 km/h. Moreover, the IMT-Advanced model can be expanded to the 2D non-stationary model for HST by introducing the movement of clusters in different propagation scenarios [38]. The massive MIMO HST channel performance is dependent on many factors; few of them are given below:

2.4.1 Cluster Evolution in Space-time-frequency (STF) Channels

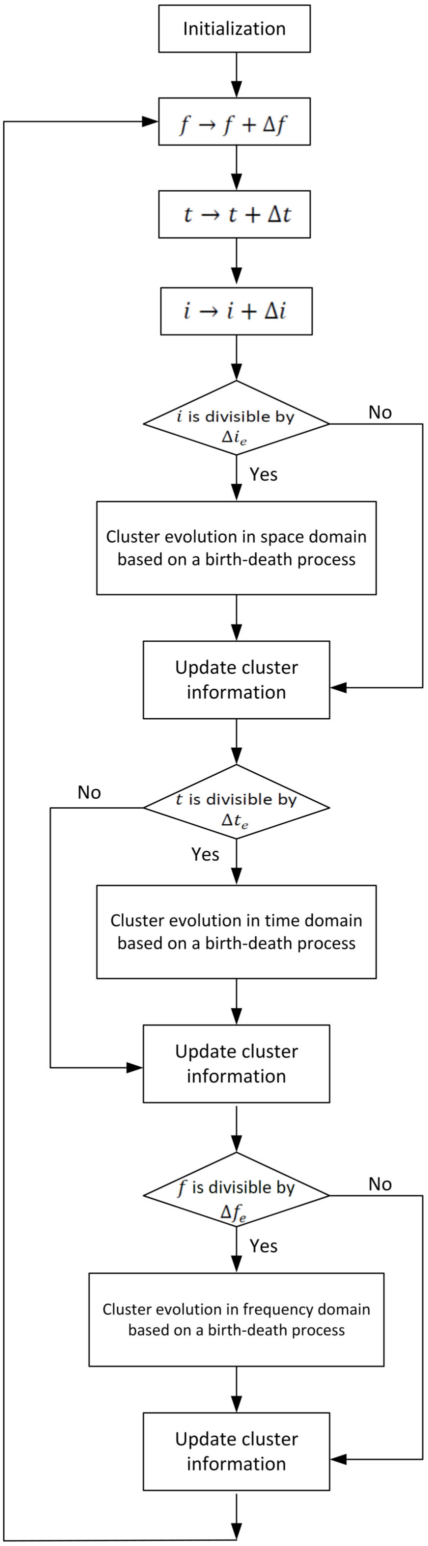


Figure 5. *The flowchart of a cluster evolution in STF domain for HST channels.*

A novel three dimensional (3D) mmWave massive MIMO high-speed train channel model has been introduced in [39], which considers the space-time-frequency (STF) non-stationarity. Characteristics of spherical wavefronts of massive MIMO channels induce the non-stationarity of a channel in space domain. Moreover, the relative modifications between the size of scatterer elements and the wavelength have a higher influence on the channel statistical data among different operating frequencies, which lead towards the non-stationarity in a frequency domain. By assuming the Saleh-Valenzuela (SV) and WINNER II channel modeling schemes, a 3D double-cluster HST channel model can be acquired [40]. All clusters have their own durable probability, and the frequency-related factors are introduced to adjust their enduring probabilities. In HST scenario, the clusters remain for a specific time period [40]. Throughout this time period, the total number of certain clusters remains consistent. When the period is over, some initial clusters may disappear and new clusters appear. The cluster evolution in STF domain for HST communications is developed in the following way: In the first step, a chain of preliminary clusters is introduced at specific time t [41]. Some parameters such as, the virtual link delay (VLD), total sum of rays, angular parameters, delay, and power of rays are required to be allocated. These parameters can be assigned through different distributions. The number of rays follows the Poisson distribution. The delay of ray and VLD of clusters are supposed to adopt exponential distribution. Furthermore, in angular parameters such as, arrival/departure angles in azimuth/elevation planes, the wrapped Gaussian distribution is followed. In the second step, to express the clustering technique more precisely, two kinds of sampling intervals are used. The first one is based on the sampling interval of a channel, i.e., Δf, Δt, and Δi in frequency, time and space domains, respectively [41]. The parameters of a channel need to be updated repeatedly during given periods. The second kind deals with the period in order to update the status of clusters. The intervals can be characterized by Δf_e, Δt_e, and Δi_e, and the birth and death process of cluster initiates during these intervals. The clustering parameters need to be updated repeatedly during the time period. All clusters have their own surviving probability. In the third step, the surviving and newly originated clusters are required to update their status. In newly originated clusters, few parameters, i.e., angular parameters, power, and delays are allocated randomly, similarly as followed in the first step. For surviving clusters, the angular parameters, power, and delays are updated against their past time instants. The cluster evolution in STF domain is shown in Figure 5. By following the aforementioned steps, the STF non-stationary characteristics of a channel model could be guaranteed.

2.4.2 Waveguide Effect

Considering the conductivity and geometrical structure of a tunnel scenario, the propagation of electromagnetic waves in a tunnel can be demonstrated in the same manner as propagating in a waveguide. In [42], it is proved that if the operating frequency is greater than a few hundred of megahertz, the waveguide effect will appear. Moreover, because of the unique physical structure of a tunnel, there exist numerous scattering and reflecting components which induce the waveguide effect in the tunnel. In [43, 44], the waveguide models are proposed, which follow the modal theory in describing the electromagnetic waves propagation phenomena inside the tunnel environment and it is equivalent to the rectangular waveguide. The transverse mode is widely used in describing the radiated field distribution of a waveguide. There exist two types of modes which propagate within a waveguide material such as transverse magnetic (TM) and transverse electric (TE) modes. Both of these modes have their own cutoff frequencies and they are dependent on the mode parametric values and tunnel size. In such scenarios, where the operating frequency is greater than the cutoff frequency, the given modes may exist within the tunnel environment. In such scenarios, where the operating frequency is in a few GHz, the distance for near regions becomes longer and as a result, the time duration in near regions turns into a higher value. Moreover, the train itself affects the field distribution when it moves within the tunnel environment. As a result, the impact of a train on field distribution and multi-mode propagation at higher frequencies must be examined in future research. The combination of massive MIMO and the mmWave channels have many advantages regarding flexibility, adaptivity, and compact dimensions. However, this combination also introduces new challenges in channel modeling. Table 3 provides the comparison of conventional wireless channel characteristics with mmWave massive MIMO channel in tunnel environment.

III. CHANNEL MODELS USED FOR PROPAGATION ENVIRONMENT

The existing tunnel models may be categorized as deterministic or stochastic channel models based on various propagation characteristics.

3.1 Deterministic Model

The leaky cable is regarded as a line of coherent point sources in the radiating mode, with each emitting a radiation pattern from the slots triggered by the traveling wave. A rigorous computation of field pattern for a finite-sized slot is much difficult. Though it may be claimed, when the LCX outer conducting sheet radius is shorter than the free space wavelength, the angle-reliant proportion is confined with the direct neighborhood of a slot, and the far field will be circularly symmetric. The dependency limit of a far field on the location is similar to the dependency of a field for the whole circumferential gap [45, 46]. The total field emitting from the radiating-mode cable is a combination of Goubau-mode field and radiated field. The Goubau-mode field exists only in the radial direction analogous to the wavelength (λ). However, it may be scattered through some nearby entities. Generally in practical conditions, the scattering from a Goubau-mode field is a most significant mechanism through which the radiating-mode cables operate. Deterministic modeling is further divided into following types as given below:

3.1.1 Finite Difference Time Domain Model

With the development of wireless communications in confined environments, it is essential to predict the field coverage and wave propagation of the wireless links in confined environments. The Finite Difference Time Domain Model (FDTD) model not only gives correct field coverage results, but it also contributes in gaining precise insights into the environment and antenna for field distribution, which is very useful in confined environments. Of course, as computer capabilities and storage capacity increase, the FDTD technique can be used to estimate high difficulties [47]. Moreover, if the antenna design is deliberated through the FDTD along the complex tunnel atmosphere, much greater spatial resolution is required to perfectly calculate the geometrical aspects of antennas. Therefore, the memory requirement and the computation time will rise significantly when uniform mesh grid technique is conceived. Although, the consideration of a subgriding scheme and a non-uniform mesh in FDTD could be practice, it may induce false results or even need to bear instability for a given subgriding scheme. In [48], a hybrid vector parabolic equation VPE/FDTD technique is anticipated to understand the radio waves propagation under rectangular tunnel environments. The FDTD method is practiced in different areas with antennas or obstacles. By utilizing the properties of the given two techniques, the numerical effectiveness can be increased. The hybrid VPE/FDTD technique is generally comprised of two parts: FDTD to VPE and VPE to FDTD. Both of the specified components have an interface, and there exists a problem with field property anticipation. For the initial part, the initial radiated field for the VPE can be estimated and deduced through FDTD results. The radiated field in the interface can be articulated through time steps and amplitude of FDTD, respectively. Through expressing the time processing from a time domain to the phase domain, the radiated field for the VPE can be obtained easily.

3.1.2 Full-Wave Channel Model

Full-wave channel model may be conceived as a substitute method, competent for solving the Maxwell's equation solutions through different boundary conditions by adopting various numerical methods, i.e., Finite Element Method (FEM) and FDTD methods [49, 50]. The FDTD technique is deliberated as a precise model which can entirely explains the characteristics of diffraction, refraction, reflection, etc., and delivers a comprehensive solution for the signals coverage through a distinct space problem. For that reason, it is highly suited for a precise study of electromagnetic propagation in different complex scenarios. The FDTD approach divides space into a regular/irregular grid and then estimates space and time approximations of the electromagnetic (EM) field strength in the same grid to discover the solution of a partial differential equation for discrete points and discrete time. This approach offers solutions in time domain which is appropriate for the software implementation [51]. On

Table 3. *Comparison between traditional wireless channel and millimeter wave massive MIMO channel.*

Property	Traditional Wireless Channel	mmWave Massive MIMO Channel
Bandwidth	Below 100 MHz	In the range of GHz
Frequency Range	Smaller than 6 GHz	6-100 GHz
Wavefront	Plane wavefront	Spherical wavefront
Antenna Elements	Normally smaller than 10	Fit for thousands
Stationarity	Web Security Service (WSS)	Non-stationary

the other hand, the FDTD obliges memory to keep the backup of basic unit components of given model and further estimates the iterations in time domain to deduce the EM propagation. Given the high operational frequency (greater than UHF) and the large dimensions of tunnel, the computational liability of traditional FDTD surpasses far away from the capability of existing electronic devices, such as computers. As a result, it has been experimenting in tunnels recently to increase the efficiency of various wireless applications by examining various techniques to reduce computing cost and runtime [52].

3.1.3 Ray-Tracing Channel Model

In a limited context, the ray tracing (RT) technique is beneficial for precise prediction of radio channel near-field computations. In the tunnel scenario, the wall material has a high impact on the radiated field patterns emitting from the transmitting antennas. The root mean square (RMS) prediction error can be significantly reduced in the RT simulations due to the diffuse scattering. In [53], the propagation environment is approximated by intensive RT simulations, and a suitable paradigm is achieved for the practical high-speed train channels at 5G mmWave band. RT simulations are used to estimate vehicle-to-vehicle (V2V) communications at 5 GHz for the line-of-sight (LoS) scenario between the transmitting and receiving antennas in different environments such as buildings, road traffic, etc., and it is proved that under obstructed vehicle environment, the higher antenna distribution can achieve better coverage with lower path loss than the smaller antenna distribution [54]. However in [55], different experiments are conducted by moving a horn antenna (used as Rx) with 30° half power beamwidth in azimuthal direction under various transmitter-receiver distances at 1.8 GHz in tunnel environment. The cross-polarization discrimination (XPD) is considered and it is concluded that maximum number of depolarized waves are originating from the sidewalls. Ray tracing approach is practiced to explore the azimuth angle of arrival (AoA) for multipath propagations. As shown in Figure 6, multipath components (MPCs) in co-polarized composition are often available at 0° (LoS direction) and 180° (reverse wireless energy transfer, abbreviated as RWET, which is effectively the reflected beam from the opposite end of the tunnel).

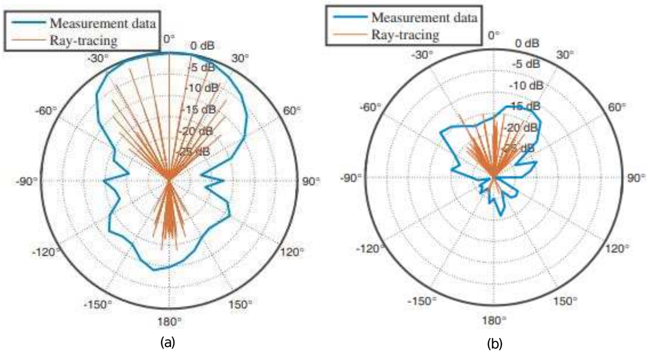


Figure 6. *The PAP's comparison between the ray tracing simulations and measurements in a Nantong tunnel, (a) Co-polarized, (b) Cross-polarized [55].*

3.2 Stochastic Modeling

A stochastic model is used for predicting the probability distribution of prospective outcomes by accounting for random irregularities in time domain. A vast number of simulations are used to generate distributions of possible outcomes, which represent the random variations in the input value. Stochastic modeling is further divided into following types as given below:

Table 4. *Recent evolutions in high-speed train channel modeling.*

Channel Modeling	Bandwidth	Speed of Train	Stochastic/Deterministic	Channel State	Ref.
Ray Tracing	mmWave	295-305 km/h	Deterministic	Coherence time, Doppler shift	[56]
QuaDRiGa-based Modeling	mmWave	495-505 km/h	Stochastic	CIR, RMS-DS, SNR, Angular spread	[45]
GBSM	mmWave	495-505 km/h	Stochastic	RMS-DS, K-factor, PDP, Angular spread	[46]
Dynamic Modeling	Sub-6 GHz	295-305 km/h	Stochastic	RMS-DS, power gain	[57]
Propagation Graph Modeling	Sub-6 GHz	195-205 km/h	Stochastic	PDP, RMS-DS, Doppler PSD, Doppler spread	[58]
FSMC	Sub-6 GHz	345-355 km/h	Stochastic	State transition probability, Correlation coefficients	[59]

3.2.1 Markov Channel Model

From the wireless propagation perspective, the communication scenario is separated into five different categories, which are intra-train, train to infrastructure, inter-train, infrastructure to infrastructure, and within the train stations. On the basis of given scenarios, various measurement campaigns have been carried out for high-speed train communications. Different cellular architectures, for example CoMP, Markov regime-switching (MRS), and distributed antenna system (DAS) are required to be deliberated in future train communication technologies [56]. Moreover, the encouraging 5G technique including massive MIMO and mmWave need to be introduced. By adopting different solutions, some HST channel models can be established, which contain large-scale fading (LSF) and small-scale fading (SSF) models. By considering the modeling methods, channel statistics, and frequency bands, the development in HST channel modeling is summarized in Table 4. Additionally, the intra-wagon channel physical characteristics resemble the indoor scenario and thus it can be modeled with some existing indoor channel models of THz and mmWave. Because of the relatively confined space of high-speed train indoor scenarios, the ray tracing (RT) channel modeling can be practiced efficiently [56]. The finite-state Markov channel model (FSMC) has been used to characterize different fading channels. However, recently it is not accessible in high-speed train scenarios because of the swiftly time-varying characteristics. In [59], an innovative FSMC channel modeling for HST is proposed. It has the capability to manifest the time-dependent process and to capture the changes of high-speed train channels. In this model, the impact of the train speed on the temporal features is demonstrated. The states of the channel are characterized by using the signal-to-noise ratio (SNR). The given model is capable to deliver an accurate sketch of time-dependent channel statistics for high-speed train scenarios and is mathematically tractable. To ensure the certainty of the proposed model, Markov chain of higher order is required to characterize the time-varying channel [58, 59]. According to the graph theory, the propagation graph models can be realized with a series of edges and vertices. The vertices signify the transmitter, receiver, and scatterer, whereas the edges signify the propagation assumptions along the vertices.

3.2.2 GBSM Channel Model

A geometry-based stochastic model (GBSM) is characterized through the specific transceiver and the geometric structure of scatterers which are expected to adopt the conclusive probability distributions. For regular shaped GBSM model, the effective scatterers are supposed to be placed on a regular shape, such as ellipse, elliptic-cylinder, 2D one-ring, and 3D one-sphere models. On the basis of geometrical shape, the channel statistics and channel impulse resource (CIR) can be designed. In [60], a stochastic scattering method is discussed to overcome the scattering phenomena from rough surfaces based on the combination of Kirchhoff and ray-optical formulations. This stochastic approach is based on tangential plane approximations of rough surfaces and it is suitable for surfaces with horizontal dimensions that are significantly larger than the wavelength of incident rays. However, if compared to the Kirchhoff method that is only effective for either highly rough or slightly rough surfaces, this method simultaneously contains both. In [61, 62], the 3D non-stationary models were considered based on Saleh-Valenzuela (SV) and WINNER II channel models in the presence of clustering property. The GBSM is established on the basis of concentric multi-ellipse channel model under the time-variant property for all model parameters. Spherical wavefronts and the presence or absence of clusters is assumed to support the mmWave massive MIMO characteristics. It should be noted that Doppler power spectral density (PSD) is usually symmetric in isotropic cases and different for angular parameters, i.e., the mean angle-of-arrival (AoA) and the angle of motion for HST have a significant influence on PSDs. Incorporating the tunnel propagation characteristics with the WINNER model, the tunnel surroundings for HST cannel can be distinguished in a 3D form such as the circular or cuboid model [63].

IV. FUTURE TRENDS AND CHALLENGES

Some contributions for designing of wireless communication channels have been deliberated in this review, which are deduced from the literature work. In addition, for the mmWave communications in non-uniform MIMO systems, the significant non-uniform multi-beams training schemes and patterns can be encouraged for further evaluation of secure and low-latency communications. In this section, different solutions are suggested to overcome the obstacles in modeling of massive MIMO radio channels. These contain the composition of Saleh-Valenzuela (SV) modeling of massive MIMO channel [64], the map-based channel modeling for the massive MIMO, the modeling of massive MIMO channels for advanced 5G special scenarios, and the channel modeling for THz communications.

1. *SV Channel Model*: The SV model is widely used to assess the system performance under the assumption of channel bandwidth when it is quite large (500 MHz). In the SV model, the total numbers of signals are assumed to pursue the Poisson distribution, and the signals with certain delays inside the cluster can be determined due to the large time resolution [65]. The IEEE WPAN has already appraised the SV model in its standards [65]. To practice the massive MIMO and mmWave scenarios in 5G systems, the ongoing SV model needs to be upgraded. By consuming the large number of antenna arrays along the array axis, the cluster evolution which is established through the birth-death process, can be introduced in the SV channel model for the massive MIMO systems [66]. In the meantime, the information of geometrical correspondence of a channel model is also required when the non-stationary characteristics along the time axis are perceived. Consequently, the cluster formation algorithm in [66] needs to be upgraded in order to consider the generation of parameters for signals within different clusters. In addition, the directional antenna systems can be extensively used in the mmWave communication channels to overcome the atmospheric absorption and path loss [67]. As a result, different channels based on directional antennas should be integrated in the given SV model. Moreover, the 3-D channels can be conceived to model new clusters against their vertical planes [68].

2. *Map-Based Channel Model*: The GBSM and METIS projects have proposed a new modeling technique for the massive MIMO networks known as map-based channel modeling (MBCM) [69]. The METIS-based MBCM model can be demonstrated based on a RT approach. It is focusing at the tracking of each ray approaching from transmitting antenna to receiving antenna. Moreover, the interactions between signals and the scattering/shadowing objects, i.e., blocking, diffraction, diffuse scattering, and specular reflection has been carefully deliberated in few studies. These scattering/shadowing objects need to be introduced randomly in given scenarios. Since each

signal is tracked through the MBCM, therefore the massive MIMO system properties, i.e., non-stationary characteristics of different clusters and spherical wavefronts can be incorporated in these models. By considering the Doppler effects at both the transmitting and receiving antenna sides, the METIS-based MBCM is capable to facilitate such environments where V2V communications for massive MIMO channels are required. However, the RT nature of the MBCM causes for a quite high complexity in channel modeling [69]. The practicability of MBCM needs to be explored further.

3. *Massive MIMO Channels for Advanced* $5G$ *Scenarios*: It is demonstrated in [70] that machine-to-machine (M2M) communications can play a vital role in future 5G communication networks, where the devices are all interlinked. The evolving applications of HST channel in 5G communication systems appeal the researchers to consider the HST channels in their future research [71]. Massive MIMO channels can be anticipated to enhance the system performance, if they are equipped at the HST or at the base station. Conversely, the high velocity of HST communication channels introduces different challenges in channel modeling. The key parameter is the presence of small stationary intervals [71]. Therefore, the channel can be considered as non-stationary. To collectively model the massive MIMO system characteristics for other advanced 5G scenarios (HST or M2M), a general channel model would be constructive if it is including the array-time evolution and Doppler effects at both the transmitting and receiving antenna arrays. These can be acquired through a GBSM framework introduced in [72] by incorporating the SV and WINNER II models. Additionally, the polarized arrays and the 3D features can be further investigated. Finally, it can be proved that each signal has its own complex gain and delay in the GBSM framework due to the involvement of SV model [72].

4. *Channel Model for THz Communications*: The spectrum of THz communications, ranging between 0.3 to 10 THz, stands between the infrared lightwave and mmWave in the electromagnetic spectrums. The THz spectrum can be regarded as the novel spectrum resource that has yet to be fully exploited [73]. However, due to the growing demands of wireless access in HST and the evolution of different semiconductor devices, the THz communication networks have gained the considerable attentions of researchers. Because of the vast bandwidth, the THz communications are expected to deliver improved data rates (100 Gbps or even more) [74]. On the other hand, because of the higher frequency bands, the signals at THz band encounter atmospheric attenuation and much higher free space path loss (PL) than those working at the microwave frequency band [75]. Thus, the THz communications are most likely to be useful in confined scenarios combined with the beam-steering systems. The channel modeling of THz communications is yet in its initial phase and quite few models of THz communications have been investigated so far. In [76], the multi-ray THz communication channel model by using a RT technique has been considered to explore the diffracted, scattered, LoS, and NLoS components interaction. The intelligent reflecting surface (IRS) is an advanced technology that allows wireless networks to design radio signal propagation in THz communications [77]. IRS is capable of dynamically modifying wireless channels to improve communication performance by smartly tuning signal reflection via a large number of low cost passive reflecting elements. As a result, the new IRS-assisted hybrid wireless network, which includes both passive and active components, is predicted to be highly promising in terms of capacity growth and cost-effective in future.

V. CONCLUSION

The demand for wireless communications in the underground tunnel and mining industries has evolved from simple signalling to human-to-human voice communications and real-time high-speed data rates. Correspondingly, the encouraging technologies have been developed from through-the-earth (TTE) transmissions to through-the-air (TTA) communications. In order to promote and assess these technologies properly, the propagation of wireless channel and modeling are crucial. On the one hand, mathematical and analytical models such as stochastic and deterministic models are established on the basis of different propagation characteristics. Main attention is devoted towards the understanding of factors influencing the channel field, mmWave, HST scenarios, and parametric adjustment to enhance the massive MIMO system performance. We thoroughly explained how angular dispersion of signals has a significant impact on channel performance, which can be properly predicted using a multimode waveguide in near- and far-field regions for underground scenarios. Finally, we have provided some suggestions for the massive MIMO systems to optimize their performance in HST tunnel and mine scenarios.

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